LEMM CORPORATION
ULTRA FAST TRACK PROJECT
MANAGEMENT & INTEGRATION

By:

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INTRODUCTION

When the Lemm Corporation was contracted to build a multi-million dollar automated packaging facility for bulk chemicals, the time frame for the project seemed impossible. Only one year was available to design, build, and have operational a brand new plant. This paper describes the techniques used to build, from the ground up, the Lemm facility where the actual time between the project kickoff meeting and the first production run was only one year and 27 days.

This paper explores the procedures used to procure, test, and install custom automated equipment for an ultra fast track project. Important players have specific roles in the project and special milestones and management procedures are needed for an ultra fast track project. The special techniques used to make the ultra fast track project a reality - such as early control system development and in-house testing of all equipment and software are described in detail.

The control system hierarchy from local PLC control to host level inventory and front office management are also discussed. Other topics include: Operator training, start-up safety, capacity planning, and system diagnostics.

BACKGROUND

In 1993, The Lemm Corporation was hired to design, build, and operate a chemical packaging facility in Memphis, TN. One of the critical elements of this contract was a short time frame in which to design and build the facility. Lemm had one year from the start of the project to have the facility operational. The facility was constructed as a "green field" project where no building or equipment existed.

PROJECT MANAGEMENT

There are three key players on the project management team - the owner, the system integrator, and the automation master specialist. The project team should not have a rigid hierarchical structure. The owner, the system integrator, and the automation master specialist have different responsibilities in each phase of the project. Acceptance of project milestones requires the concurrence of all three.

OWNER

The owner's role is very important to the ultimate success of the automated system. The owner has the business need which must be solved with the automated system. Too often the business need gets lost in technical details as the system is being developed. The owner has to foot the bill and live with the system after it is installed. If the automated system functions perfectly but does not fulfill the business need, it is a failure.

The owner is in the best position to make decisions which affect the capital cost of the system versus ongoing operating expense. For example: Will automating a filling operation at a cost of $1 million eliminate enough future operating expenses to make it cost effective?

The owner's role in this project was assumed by John Lemm of The Lemm Corporation, Memphis, TN.

SYSTEM INTEGRATOR

The system integrator is a key player in the ultra fast track project. The system integrator provides expertise in all aspects of system automation. Various pieces of equipment and subsystems will be fused together into a single automated system under the guidance of the system integrator. The system integrator must scrutinize the interfaces between vendors both mechanical and electrical to make sure that nothing is left out or misinterpreted. One of the most common problems with integrating equipment from various suppliers is overlooking something at the interface points. Each vendor assumes that the other vendor is handling an element and neither of them does. For example, the loading height of a machine is 31" and the conveyor feeding it is 30" high, or a handshake signal required by a machine is not supplied by the conveyor's PLC.

The system integrator is also the technical expert who reviews drawings and submittals for the owner. The owner seldom has in-depth experience in automated systems and relies on the system integrator to interpret the technical issues. The system integrator is responsible for the in-house tests performed at the various suppliers and facilitates the flow of information between the various contractors. In an ultra fast track project, nothing is assumed. One supplier who is less than candid on an issue can seriously affect the project. The system integrator is continually monitoring the progress of all suppliers anticipating problems and working out solutions before they become obstacles in the project's path.

The system integrator for the Lemm project was Gerry von Stroh, Tekdata Systems, Parker, CO.

AUTOMATION MASTER SPECIALIST

This is a new role required by ultra fast track projects. The automation master specialist provides in-depth experience in the use of real time modeling for automated systems. Modeling is used to replace components of the system needed but not yet available.

The automation master specialist provides traditional simulation expertise in the early stages of the project. The automation master specialist takes the proposed design and equipment layout and verifies that it meets the requirements of the project. For example, in the Lemm project, the automation master specialist determined the storage requirements by running the

1992 production year through the model and using the results to determine the size and type of equipment needed.

The automation master specialist adds detail to the simulation model and transforms it into an emulation model for use in testing the control software. One of the enabling technologies for ultra fast track projects is the ability to start programming the control logic before all of the system details are finalized. The process of programming the control logic adds dynamics to the system. System elements that were overlooked in the design become obvious on an animated display.

The automation master specialist assists in the in-house tests by using the real time model to supply any signals supplied externally to the subsystem under test which are not available. The automation master specialist also takes this opportunity to create an "as built" model of the subsystem and verify that the subsystem "as built" will properly perform its function in the overall system operation. The automation master specialist is responsible for the test of the host computer system. The in-house test of the host computer system draws extensively upon the scenarios established during the design phase to prove system performance.

During equipment installation, the automation master specialist sets up the diagnostic monitor to assist in testing the proper installation of subsystems by testing the wiring and communications links and verifying the operation of the system is the same on the plant floor as it was in the in-house tests. The automation master specialist also uses the real time model to provide operator training and answer questions that arise during the installation process. The real time model is also used as a diagnostic monitor which is left with the system to help in ongoing maintainence.

The automation master specialist for the Lemm project was Max Hitchens, HEI Corporation, Carol Steam, IL.

STRATEGY

On an ultra fast track project many tasks must occur simultaneously. The building, equipment, and software all have to be designed and built on parallel paths. In a traditional design/build approach the overall design is completed before the any construction begins. The detailed design of a multi-million dollar facility usually takes a year or more. One year was all that was available to design, build, and have operational the entire Lemm facility. The project team implemented a strategy based upon the following elements:

1. Performance contract

2. Payment based upon demonstrable accomplishments

3. Rigorous third party testing

4. Acceptance upon proof of performance

PERFORMANCE CONTRACT

An important element of the ultra fast track project is the contract with the suppliers and subcontractors. All contracts should be performance based. That is, the contract specifies the functioning result of the equipment or subsystem as the deliverable for contract

completion. For example, filling 2 containers a minute, unloading 50,000 lbs. of bulk product per hour, storing 40 unit loads per hour, etc. are specified as the result of contractual performance.

Intermediate payments are made based upon milestones, but the contractual obligation is for specific operational results. The contract must have provisions for changes. The ultra fast track project requires issuing contracts before the design is complete and all of the detailed requirements known. It is necessary to establish a contractual relationship which anticipates deviation from the baseline documentation. The deviations should have no cost impact unless the changes increase the scope of the project.

For example, the site preparation may be started before the exact building footprint is determined. The contract could include a preliminary drawing with the cost of preparing the site to that drawing and the cost ($ per ton) for deviations which require additional work. In this example, changes in the building footprint which do not effect the overall amount of dirt moved have no effect on the cost of site preparation.

All changes chargeable to the project require notice and documentation. A subcontractor or supplier notifies the owner if a change increasing the scope needs to be made. The owner approves the change and the contractor documents the additional work required by the change for review at the end of the project.

IMPORTANT: The contract should require that the additional cost for changes only be paid upon completion of contractual obligations. In an ultra fast track project, the project team does not have the time to scrutinize change documentation during the intense testing and startup periods where nearly all chargeable changes occur.

One of the toughest elements of the contract is the default clause. In an ultra fast track project, a delay by a vendor of only a month can wreak havoc upon the project. A strong default clause with liquidated damages should be drafted and the project team must have a backup plan at all times to handle a non-performing vendor.

PAYMENT BASED UPON DEMONSTRABLE ACCOMPLISHMENTS

The contract is performance based so that fulfillment of the contractual obligation is not complete until after the system is installed and operational. Very few suppliers are capable or willing to carry the expenditure needed to fulfill the contract for the entire period of time necessary to make the system operational. Therefore, progress payments are usually made during the course of the project. The progress payments should be structured so that they are made based upon demonstrable accomplishments - milestones.

The progress payments are made upon completion of milestones which provide concrete evidence of the results of a value added effort by the supplier. For example, the receipt of the steel for the storage system should not be a milestone. However, the fabrication of the steel into a storage bay which is then erected and demonstrated is a demonstrable accomplishment.

Properly defining the milestones is very important to the project. The motivating force for a corporation is largely economic. A corporation performs work to receive payment. The milestone is the goal to which the supplier works toward, and which, when reached provides payment as a reward. Pavlovian but very effective. Suppliers or contractors demanding

prepayments should be avoided. Prepayment removes one of the big levers which the project team has to assure the timely performance necessary for an ultra fast track project. Experience shows that vendors who are prepaid are more likely to default on the contract by not providing timely performance than those who receive payment after the service is performed.

RIGOROUS THIRD PARTY TESTING

Another necessary element for the ultra fast track project is the ability to monitor the performance of all suppliers. One of the biggest problems with ultra fast track projects is lack of timely supplier performance. Most contractors are not used to performing to a rapid and rigid schedule.

Tests should be scheduled to demonstrate supplier accomplishments on a regular basis. These tests are administered by an independent third party usually the systems integrator or automation master specialist. These individuals have experience in the process of producing an automated system. The owner knows what the end result should be, but usually does not have the experience necessary to determine if the project is on schedule at any given time. DO NOT rely on the contractors' statements as to the progress of their work. Continual verification of performance by experts must be done throughout the project.

PROJECT TIP: Some companies, like some individuals, tend to procrastinate on a job. Schedule tests in advance of the time when the element is actually required. If the company does not have the element ready for test when promised adjust the test schedule accordingly. If a contractor routinely slips two weeks on each test, modify the test schedule so that tests are run two weeks earlier. An ultra fast track project has insufficient time to modify the behavior patterns of a contractor, so that, once the project is started, the team must work with the contractor's foibles and characteristics.

ACCEPTANCE UPON PROOF OF PERFORMANCE

The completion of any aspect of the project must be based strictly upon proof of its performance. Simple delivery or installation is not sufficient. The component or subsystem must be delivered, installed, and producing quality at the rate specified.

The question which must always be answered is: Does the system satisfy the needs of the business? A line may produce at the rate required but not produce quality products. The system is not acceptable until it is capable of performing to the requirements of the business.

PROJECT MILESTONES

The success or failure of ultra fast track projects hinges upon the definitions and enforcement of milestone points. There are six basic milestones for each vendor on the project.

1. Preliminary drawings.

2. Control software completion.

3. In-house test.

4. Installation completion.

5. "As built" documentation.

6. Reliability test.

These milestones are not always appropriate for every vendor. Vendors which supply smaller subsystems will have fewer milestones to which the basic milestones have been reduced. Some suppliers of large and complex systems will have additional milestones to assure timely and proper performance.

PRELIMINARY DRAWINGS

The preliminary drawings are the documents which provide the baseline for what each vendor will supply. They are used to review the scope of the vendor's tasks and as discussion focal points on the system's operation.

These drawings are not intended to be final "build to spec" drawings. You cannot expect that in 2-3 weeks a complete set of drawings will be produced which detail a complex automated system and covers all contingencies. The contract is based upon performance. Acceptance of preliminary drawings or agreement with a vendor on an approach did not relieve that vendor of the obligation to meet the broad performance criteria of the contract. Acceptance of this milestone is the responsibility of the system integrator with concurrence of the owner and the automation master specialist.

CONTROL SOFTWARE COMPLETION

The completion of this milestone is required before any of the subsystems can begin in-house testing. This milestone is one of the key elements to the success of the ultra fast track project. The preliminary drawings only present a static picture of the system. The control software adds dynamics to that picture. Observing the system in operation on an animated computer display enables everyone to see precisely how the system will operate.

Control software development forces closure on some important issues. The control software cannot be completed until all interfaces between vendors have been defined. The control software must also operate the system in degraded or manual modes. This assures that the operation of the system in automatic, semi-automatic, and manual modes has been tested and reviewed.

Operator interfaces are part of the control software development. Interaction between the operator interface and a real time model shows the ergonomics of operating the system. The

system operation must be completely defined in order to complete development of the control software.

Acceptance of this milestone is the responsibility of the automation master specialist with concurrence of the owner and the system integrator.

NOTE: This milestone and its placement on the time line of the project represents a significant departure from the way automated systems have been traditionally developed. Completion of the control software early in the project contributed significantly to Lemm's success.

IN-HOUSE TEST

The in-house test is the test of a subsystem or piece of equipment before its shipment to the job site for installation. The test is conducted using the real subsystem and its controls.

For the in-house test, the equipment is staged at the vendor's location. A close inspection of the equipment is made to check for construction quality, e.g. are the welds solid, all pinch points guarded, devices and wires labeled properly, etc. The PLC is connected to the equipment and the subsystem exercised using the operator interfaces in as close to real conditions as possible. The actual equipment operators are used whenever possible. In this manner, equipment operators gain experience on operating the equipment and provide essential feedback on ergonomic issues. Subsystem functionality and throughput rates are verified.

While the equipment is being exercised it is validated against the model to determine any discrepancies between the "as built" and "as designed" subsystem. As each subsystem is tested the model is updated to reflect the "as built" subsystem.

The in-house test is the last milestone before shipping a subsystem for installation. At the in-house test, the vendor is required to demonstrate that the subsystem is completely functional and ready to ship.

There are two types of vendors - equipment vendors and software vendors. The equipment vendors are required to stage the entire subsystem, connect up the controls, and run the actual equipment to demonstrate its functionality. A real time model assists by enabling the testing of subsystems independently of each other. The model is used to mimic the operation of the remaining subsystems while only the subsystem under test is wired to the actual equipment.

IMPORTANT: As the "as built" model is finished for each subsystem, the model should be rerun in simulation mode to verify that none of the changes between the "as designed" system and the "as built" system affect the overall performance.

After a subsystem has passed the in-house test it is ready to be disassembled and shipped to site for installation. Acceptance of this milestone is the responsibility of the system integrator with concurrence of the owner and the automation master specialist.

INSTALLATION COMPLETION

After the in-house test, the equipment is sent to the site for installation as soon as the facility is ready to receive it. The installation proceeds with subsystems being installed concurently until all equipment and subsystems have been completely installed. The installation is then checked for quality and completeness of both mechanical and electrical components. Interfaces between subsystems and equipment which have not been connected before should be carefully scrutinized.

The real time model is used to validate field wiring and communications between subsystems. As each subsystem is installed on the job site, the wiring is tested for correct re-assembly by activating and observing signals on the model running in monitor mode.

When the entire system is installed and operational, this milestone is complete. Acceptance of this milestone is the responsibility of the system integrator with concurrence of the owner and the automation master specialist.

"AS BUILT" DOCUMENTATION

The "as built" documentation is very important to the long term maintenance and operation of an automated facility. Careful review of "as built" documentation requires once again inspecting the entire system with the final drawings in hand to verify that the drawings are complete and do in-fact match the system as it was installed. The verification and acceptance of the "as built" documentation is one of the more time consuming milestones of the project. This is the last chance to catch mistakes and errors built into the system. The next people who will review the documentation and compare it to the actual system will be maintenance personnel and often in a crisis situation were poor documentation can have an enormous cost in lost production.

Acceptance of this milestone is the joint responsibility of the systems integrator, owner, and automation master specialist.

RELIABILITY TEST

The reliability test is the final milestone of the project. It is the final proof that the system will meet the performance requirements of the contract. The reliability test is conducted entirely by the system operators. No contractor or equipment suppliers are allowed to intervene.

The reliability test on the Lemm project consisted of two parts. First, two consecutive shifts without a single jam or failure causing operator intervention were required. Any failure or jam was noted and the responsible contractor obligated to analyze the failure and correct the underlying problem. Just clearing a jam is insufficient to correct the problem. The cause of the jam must be determined and the underlying problem fixed. This portion of the test was observed by the contractor or supplier.

The second part of the reliability test required 95% up time at contractual performance levels for a five day period. This portion of the test was conducted independently of the contractors or suppliers. A log was kept of the activity for the 5 day period, specifically detailing the failures that occurred and the actions taken to correct them. This log was reviewed by the contractor, owner, and maintenance personnel to determine whether excess downtime was

caused by equipment flaws which should be fixed by the contractor, insufficient or improper spare equipment which is the responsibility of the owner, or improper maintenance techniques which can be resolved by additional training.

Acceptance of this milestone was the responsibility of the owner with concurrence of the system integrator and the automation master specialist.

The time table for the Lemm project is shown as follows:

LEMM PROJECT TIME TABLE

	September	October	November	December	January	February	March	April	May	June	July	August	September
Facility	Site Layout		Site Preparation		Concrete Work			Building Erection		Electrical/Mechanical			Occupancy
Equipment	Design		Fabrication					In-House Testing		Installation		Integration	
PLC Controls	Design	Programming				Emulation Testing		In-House Tests		Installation		Integration	
Host Computer	Requirements Document				Programming					In-House Tests		Installation	Integration
Modeling	Simulation				Emulation				Model Verification	Monitoring/Diagnostics			

HOST COMPUTER SYSTEM

The host computer subsystem presents unique challenges. The host computer development usually takes as long or longer as the remainder of the project. As such, it is necessary to have a plan for starting up the facility in a semi-automatic mode without the host computer.

The host computer programming requires a team of dedicated professionals. Three preliminary documents are required to describe the user interface, architectural layout, and automated system interface. These documents should be produced simultaneously and be available very early in the project.

USER INTERFACE

The user interface document is the description of each user screen with a sample layout. Each field on the screen should be described with all possible entries in that field listed and a brief description of each.

ARCHITECTURAL LAYOUT

A drawing of the system hardware architecture with a description of each piece of equipment and its function in the system should be provided. Also, a drawing of system software architecture with a description of each piece of software both custom and purchased and its function in the system should be provided.

AUTOMATED SYSTEM INTERFACE

The automated system interface is the design document which contains all of the interface points and messages which are transferred between the host computer and the PLC on the factory floor. This document is used by the control logic programmers to interface with the host computer.

The milestones for the host computer subsystem vary greatly depending upon the functions required of the host computer. For example, the Lemm host computer handled the following:

1. Purchasing of consumables.

2. Inventory tracking

3. Production scheduling

4. Customer orders

5. Bar code printers

6. Bar code scanners

7. RF terminals

8. Operator terminals

9. General purpose printers (reports, etc.)

10. Speciality printers (Bills of Lading, etc.)

The owner, system integrator, and automation master specialist must review the system requirements with the host computer vendor and establish intermediate milestones for host computer subsystem development. Milestones should be no further than 2 months apart.

In cases where real time data or control is exchanged between the PLC and host computer, a PLC and a real time model needs to be set up for use by the host computer programmers.
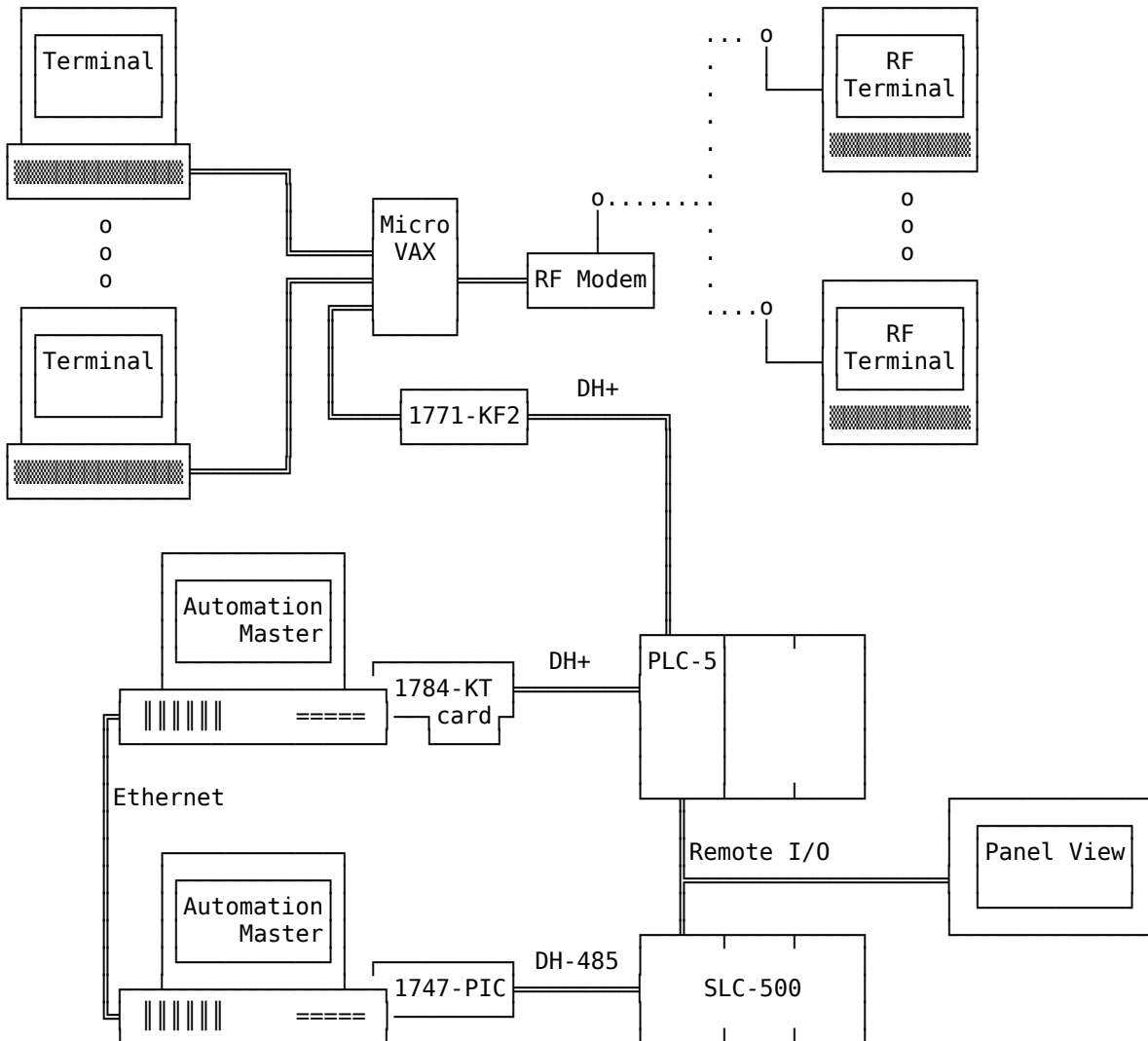
HOST COMPUTER IN-HOUSE TEST

The final milestone for the host computer system prior to its shipment and installation in the field is the in-house test. This test is crucial to the success of the entire project because it is the last (and generally the only) opportunity for the entire computer and control hierarchy to be tested. A lab must be set up with all of the host computer equipment including operator terminals, printers, barcode printers, RF terminals, etc. Also connected to the host computer is the PLC (or network of PLCs), man-machine interfaces, and real time models to duplicate the equipment being installed in the field.

The host computer in-house test has a dual purpose. It checks out the functionality of the host software and more importantly, it verifies that the automated system as a whole will meet the business requirements which prompted the automated system in the first place. For example, can orders be entered on the host computer, scheduled for production, automatically produced, and shipped to the customer smoothly with the tools provided at the host computer level and the plant level?

Actual production personnel should be used in the host computer in-house test if possible. The test provides an opportunity for production personnel to be trained in advance and gain experience in operating the system. It also demonstrates that the host computer system can be operated by ordinary production personnel. The operators should be instructed not to "baby" the system. They should be requested to try and "break" the system with the only stipulation being that they carefully keep track of the actions they take so that those actions can be duplicated by the host computer programmers in order to fix any problem uncovered.

In the case of the Lemm project, the computer in-house test was three days of actual production. This approach was very successful. After the first two days of testing it was evident that the host computer software was not robust enough to withstand the Lemm operators. So the first attempt at the in-house test was abandoned and the host computer programmers left with a 100 item punch list to fix. The second attempt a month later was successful. The hardware configuration used by Lemm for the host computer in-house test follows:

HOST COMPUTER IN-HOUSE TEST CONFIGURATION

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  Terminal                              ... o        RF
                                           .   o ── Terminal
  ▓▓▓▓▓▓                                     .        ▓▓▓▓▓▓
         ────┐              o........        .
   o         │  Micro                        .         o
   o         ├──  VAX   ──── RF Modem ──      .         o
   o         │                               .         o
  Terminal ──┘              ....o             RF
                                    o ──── Terminal
  ▓▓▓▓▓▓        1771-KF2    DH+              ▓▓▓▓▓▓


  Automation
   Master
                            DH+   ┌─ PLC-5 ──┐
 ║║║║║║  ═════  1784-KT ────      │          │
                card             │          │
 Ethernet                        │          │
                                 └──────────┘
                                  Remote I/O ──── Panel View
  Automation
   Master
                 DH-485           SLC-500
 ║║║║║║  ═════  1747-PIC ────
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The completion of the host computer in-house test proves that the host computer software, PLC logic, and man machine interfaces can withstand use by actual operators under field like conditions.

ULTRA FAST TRACK PROJECT TECHNIQUES

The ultra fast track project incorporates some new techniques which are not normally used on projects. These techniques represent major deviations from standard project procedures.

AUTOMATION MASTER SPECIALIST

An automation master specialist was added to the project team. In most projects, the owner works with a system integrator to manage the project. This pairing has one flaw. system integrators seldom have detailed experience in real time modeling. An automation master specialist has experience with testing automated systems at all levels from the use of simulation to validate the design, the use of emulation to test control software, and the use of on-line diagnostics to verify "as builts" and proper system operation.

EARLY CONTROL SOFTWARE DEVELOPMENT

The milestone for control software completion was moved up on the time line from after installation where it is normally placed to before in-house testing. This forces important decisions on how the system is going to operate to be made while the equipment is being designed and fabricated instead of after the equipment is installed and an attempt is being made to make it operational.

In traditional projects, the software programming is not started until the equipment has been built because the equipment is used to debug the software. This approach slows down the project in two ways. First, the software debugging time is placed on the critical path of the project. Since the time required to debug the control system is typically 30% of the control software development time, placing this time on the critical path of the project can extend the overall completion time by up to 30%.

The second way the project is slowed down by using the equipment to debug the software is that it ties up the equipment so that it cannot be used for other purposes such as production tuning and testing. By not having the equipment available for production tuning and testing until after the software has been debugged adds another 20% or more to the project completion time.

RIGOROUS IN-HOUSE TESTING

All subsystems are rigorously tested at the contractor's facility before they are allowed to be shipped to the job site. At the contractor's facility all of the equipment and personnel which the contractor has available are available to work on the subsystem. After the subsystem is shipped to site, only a small field team with limited tools accompany it. Consequently, the solution to problems encountered in the field are hampered by the lack of available tools and personnel and the necessity of working around other vendors.

DO NOT succumb to inevitable complaints by vendors that they are wasting time by assembling the subsystem for the in-house test, then disassembling it, only to reassemble it again on the job site. The biggest mistake made on the Lemm project was, after giving vendors a punch list of items to be fixed as a result of the in-house test, obliging their request to be allowed to fix these items while the equipment was being disassembled for shipment. The equipment arrived at the job site with a majority of the punch list items uncorrected.

DO repeat the in-house test as often as necessary until the subsystem performs 100% before it leaves the vendors facility. There will be enough problems to fix in the field when the subsystems are connected together for the first time without the necessity of dealing with problems which could have been more easily fixed in the vendor's facility.

REAL TIME MODELING

Real time modeling is a critical tool necessary for the simultaneous execution of different tasks on the project time line. The real time modeling software used on the Lemm project was Automation Master which is the only modeling software package available which can be used for the entire life cycle of the project. An Automation Master model operates in various modes at different stages of the project.
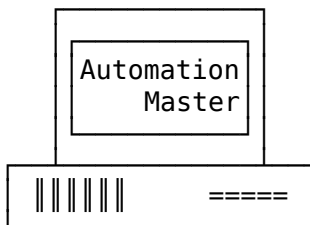
SIMULATION MODE

In simulation mode, the real time model acts as a stand alone system. The model is used to test the proposed system design and provide capacity planning for the automated facility.

For example, on the Lemm project, one of the unknown elements was the storage subsystem which consisted of an AS/RS crane feeding flow rack storage. The storage requirement was a 10 day supply of product to cover any process perturbations and change over situations. There were four different sizes of storage bays required by the product. The model was used in simulation mode to run one years worth of historical production to determine the size and mix of storage bays required.

Real time simulation is not traditionally used for design type simulations. The advantage of using a real time simulator during the design phase of the project is the reusability of the model. Since any detailed model takes time to develop, maximizing its use is important. Using traditional next event simulators, the simulation model can be used in the design process to make basic design decisions but it cannot be used as a tool to test software or train operators. Real time simulation is not the fastest or easiest way to do a "quick and dirty" design phase simulation, but due to its intrinsic reusability, it is the most economical approach for projects which are carried through to completion. Ultra fast track» projects have a funded budget do not depend upon a specific design to get the project approval.

The set up of Automation Master in simulation mode is shown below:

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│ ┌─────────────┐ │
│ │ Automation  │ │
│ │     Master  │ │
│ └─────────────┘ │
└──┬───────────┬──┘
┌──┴───────────┴──────┐
│ ▏▎▍▏▎▍▏    ═════     │
└─────────────────────┘
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In simulation mode, Automation Master acts as a stand alone simulator and does not require any other equipment to operate.

EMULATION MODE

One of the unique characteristics of a real time simulator like Automation Master is its ability to accept decisions made by external devices. This allows the model to emulate the automated equipment to the control system. The control system is programmed as it normally would be and the model used to test it. Thus, the control software programming can be started early in the project since the real time model replaces the actual equipment for debugging purposes.

In the Lemm project, the emulation model was built section by section as soon as the design for the section was stable. The vendors of the software were supplied the model for use in testing of their software. The completion and test of the control software under emulation was a significant project milestone with a substantial payment to reward its completion.

Emulation models are extremely detailed, the stroke of each air cylinder is input into the model with the time required to extend and retract. All discrete components - photo eyes, limit switches, etc. are placed in the model exactly where they will be positioned on the actual equipment.

The process of modeling the equipment and programming the software brings out many detailed design questions which can be answered and problems solved before the equipment has been completely fabricated.

All of the operator stations and push button panels are included in the model. By laying out the operator panels in the model, the ergonomics and operating sequences are brought to the attention of the programmers. The panels can be easily rearranged before any holes have been punched in cabinets.

The man machine interfaces can also be tested using the emulator. The control software runs in the PLC, the Automation Master model acts as the equipment, and the man-machine interface is used to interact with the simulated equipment. This configuration is also used for operator training.

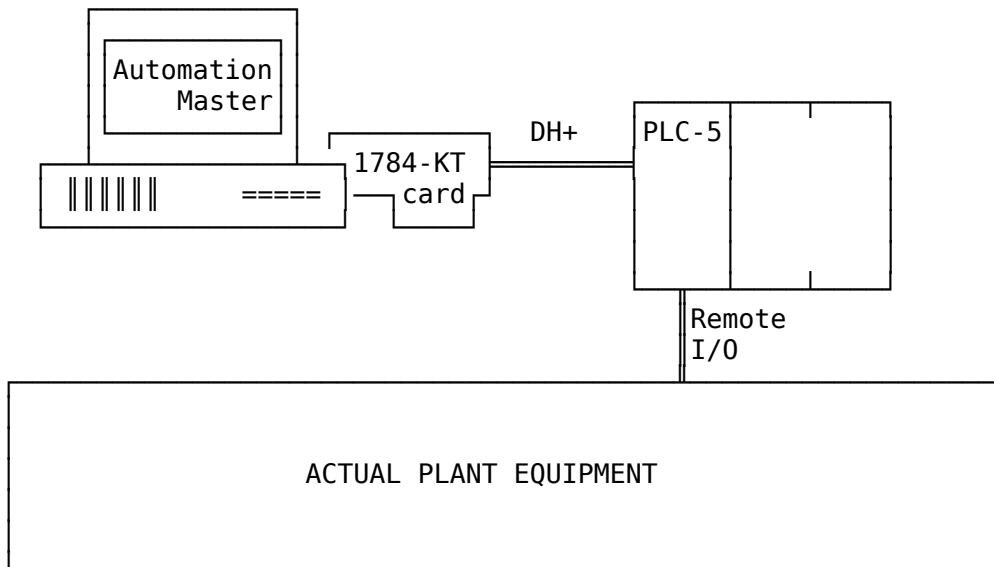An example of the set up of Automation Master in emulation mode is shown below:
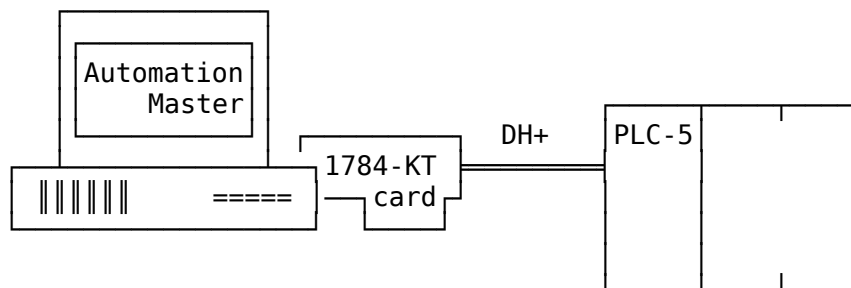
In emulation mode, Automation Master is connected to the PLC which controls the equipment and mimics the operation of the equipment by reading the output image from the PLC and responding with the input image containing the state of the inputs as if the actual equipment were attached.

MONITOR MODE

Automation Master acts as a diagnostic monitor on the installed system. In this mode, the real time model runs in parallel with the actual system. Each activity in the real system is compared with the activity in the model. If the activities concur or are within the specified tolerances, the system is operating normally. If the activities are different or outside of specified tolerances, an alarm is generated. Since the model is "perfect," there are no jams or equipment failures in the model. Any jam or equipment failure causes an activity which does not correspond to the activity in the model and generates an error on the diagnostic monitor.

An example of the set up of Automation Master in monitor mode is shown below:

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        ┌─────────────────┐
        │  ┌───────────┐  │
        │  │Automation │  │                        ┌──────┬──────────┐
        │  │  Master   │  │              DH+        │PLC-5 │          │
        │  └───────────┘  │          ┌──────────┐   │      │          │
        ├─────────────────┤          │1784-KT   │   │      │          │
        │║║║║║║║║   ═════  ├──────────┤  card    ├───┤      │          │
        └─────────────────┘          └──────────┘   │      │          │
                                                    └───┬──┴──────────┘
                                                        ║ Remote
                                                        ║ I/O
                         ┌──────────────────────────────╨────────────┐
                         │                                            │
                         │                                            │
                         │          ACTUAL PLANT EQUIPMENT            │
                         │                                            │
                         │                                            │
                         └────────────────────────────────────────────┘
```

In monitor mode, Automation Master is connected to the PLC that controls the equipment. The state of all outputs and inputs are read and compared with the activity in the real time model. Errors are displayed on the graphics display.

The monitor mode also has a field verification feature which enables the "as built" system to be compared with the model. The verification prints out the difference between each activity in the system and the activity in the model. This allows the model to be modified to correspond exactly to the real system and close the loop in the modeling process.

The verification feature causes each discrete activity - photo eye, limit switch, etc. to print the difference between the actual activity of the equipment and the activity in the model to a log. The log is then used to create an "as built" model to match the "as built" system. The log provides the difference in both time, and if applicable, distance between the signal transition in the model and the signal transition in real system.

The variance log will give a LEAD time value, if the model signal transition occurs before the real signal transition, or a LAG time value if the model signal transition occurs after the real signal transition. An example of the verification log is shown below:

```
10/11 13:02:39 ON  PE01101    -01.177 LAG        - 1.345U
10/11 13:02:44 OF  PE01102    +00.422 LEAD       + 0.844U
     └──────┬──────┘  │         │        │          │
            │         │         │        │          │
DATE & TIME │         │         │        │          │
POLARITY ───┘         │         │        │          │
SIGNAL NAME ──────────┘         │        │          │
TIME VARIANCE ──────────────────┘        │          │
DIAGNOSTIC MESSAGE ──────────────────────┘          │
SUPPLEMENTAL INFORMATION ───────────────────────────┘
```

The date and time field contains the date and time from the system clock when the log data was output. The polarity field contains the polarity of the transition either ON or OFF which caused the log. The signal name is the mnemonic for the signal used in the model. The time variance is the time in seconds that the model signal differed from the real signal. A

LEAD diagnostic message indicates the signal in the model occurred before the real signal. A LAG diagnostic message indicates the signal in the model occurred after the real signal. The supplemental information field contains the variance between the model signal and the real signal expressed as a distance. The distance variance is the distance which must be added to the model to exactly match the "as built" system.

The real time model is refined and improved throughout the simulation and emulation processes. After verification the model is identical to the real system, so all tests performed using the model have identical results to the real system.

MIXED MODE OPERATION

Another of the unique advantages in using a real time simulator is the ability to run a model partially in simulation mode and partially in emulation mode. For example, the filling systems were custom built for the Lemm project. Their proper operation was critical to the overall system performance. During the in-house test of the filling system, the PLC-5 which ran the material handling system and communicated with the VAX system was connected to the SLC-500 which ran the filler. The model was attached to the PLC-5 and the actual equipment attached to the SLC-500. In this manner the actual operation of the filler could be tested as well as its interaction with the rest of the system. The filler in-house test configuration follows:

FILLER IN-HOUSE TEST CONFIGURATION
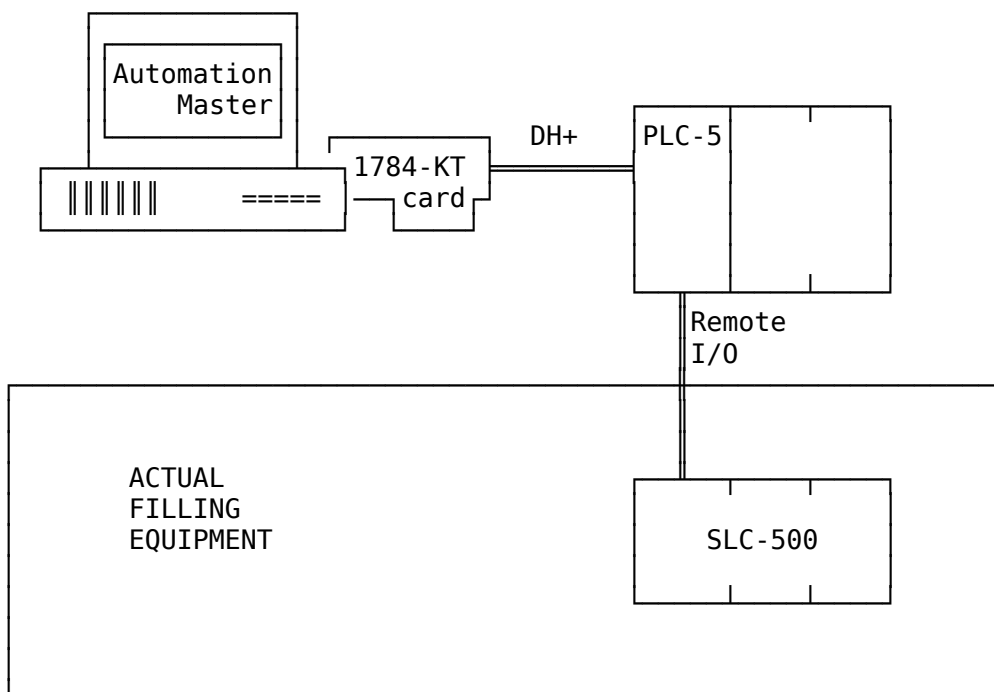
SYSTEM ARCHITECTURE CONSIDERATIONS

The system configuration must allow for parallel development and independent testing on ultra fast track projects. This section describes the system architecture used on the Lemm project to independently develop and test the various subsystems.

The system architecture was structured to enable the in-house testing at multiple vendor sites to be conducted concurrently. Each subsystem was built independently with its own remote I/O rack and control cabinet. This enabled the subsystem to be tested by simply plugging in

the PLC to the remote I/O connector on the rack. An Automation Master model was used to supply any interface signals the subsystem needed.

During the in-house test, the model and PLC were connected to the subsystem to be tested. All other equipment, except for the subsystem under test was emulated. The I/O from the subsystem under test was real with the Automation Master model supplying the I/O for the remaining equipment. In this manner, each subsystem could be tested independently. At the same time the impact that the subsystem would have on the remainder of the system could be determined.

The ladder logic for each subsystems was written by different programmers and run on one PLC. In order to enable simultaneous development, each programmer used different program and data files for their logic. For example: the host computer interface was written in program file #1 and used internal files - B3, T4, C5, N7, etc. The bulk handling logic was placed in program file #2 and used internal files - B13, T14 C15, N17, etc.   The conveyor logic was written in program file #3 and used internal files - B23, T24 C25, N27, etc. All interfaces between the different programs were documented and used data from common internal files.

A spare of each PLC was purchased with a rack and power supply so that the different software developers could have access to a PLC to test their logic and sufficient PLCs were available to conduct in-house tests and logic tests simultaneously. During the intensive in-house test times another PLC was borrowed so that sufficient PLCs were available to operate the subsystems and perform software tests simultaneously.

 A typical test configuration for a subsystem in the in-house tests is shown below:

SUBSYSTEM IN-HOUSE TEST CONFIGURATION
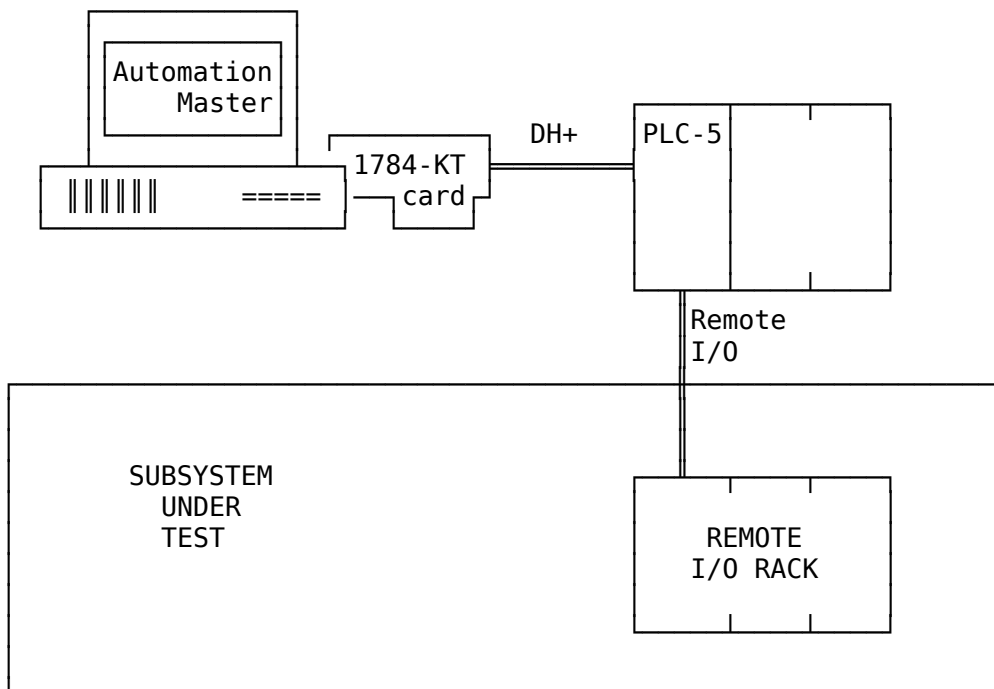
The PC with the Automation Master model and a PLC with the program was taken to the vendor's site where it was connected to the subsystem for the in-house test.